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TECHNICAL PAPER to be presented at the
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ABSTRACT

The in situ ply strengths in several composites were calculated using a computational procedure developed for this purpose. Laminate fracture data for appropriate low modulus and high modulus fiber composites were used in the laminate analysis in conjunction with the method of least squares. The laminate fracture data were obtained from tests on Modmor-I graphite/epoxy, AS-graphite/epoxy, boron/epoxy and E-glass/epoxy. The results obtained show that the calculated in situ ply strengths can be considerably different from those measured in unidirectional composites, especially the transverse strengths and those in angleplied laminates with transply cracks.

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Key words: fiber composites, graphite composites, boron composites, glass composites, fracture stresses, uniaxial data, in situ ply strength, stress analysis, laminate analysis, least squares method, computer program.

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INTRODUCTION

It has been suspected for some time now in the fiber composites community that uniaxial ply strength in angleplied laminates (in situ ply strengths) may be considerably different from those measured in unidirectional composites under uniaxial loading (uniaxial ply strengths). A major reason for this suspicion is that the predicted fracture stresses of angleplied laminates, based on uniaxial ply strengths, are generally considerably lower than measured data. To obtain better agreement between theory and experiment, investigators have either arbitrarily increased the transverse and shear strengths by some factor (ref. 1), modified them in some manner (ref. 2), or neglected them completely (refs. 3 and 4). A procedure, therefore, is needed which can be used to assess the in situ ply strengths and compare these with uniaxial values. To meet this need, an investigation was conducted at NASA Lewis Research Center with the objective of obtaining an initial assessment of in situ ply strengths.

The investigation included both experimental and theoretical aspects with emphasis on developing a formal procedure to determine the in situ ply strengths indirectly. The experimental program consisted of testing quasi-isotropic angleplied laminates from Modmor-I/epoxy, at various load angles. The laminate configurations were: $(0/\pm60)_s$, $(0/\pm45/90)_s$, $(0/\pm30/\pm60/90)_s$ and $(0/\pm22.5/\pm45/\pm67.5/90)_s$. Each of these laminates was tested at load angles of 0^o, 15^o, 30^o, 45^o, 60^o, 75^o and 90^o to the 0^o-ply direction. The major portion of this work was reported in reference 2. The theoretical part is described in detail herein. The analytical effort consisted of using laminate analysis in conjunction with the method of least squares to determine the in situ ply strengths using fracture stress data from the above quasi-isotropic composites and data available in the literature for AS-graphite/epoxy, boron/epoxy and E-glass/epoxy.

THEORETICAL APPROACH AND GOVERNING EQUATIONS

The approach used to calculate the in situ ply strengths is as follows. It is assumed that the ply combined-stress strength criterion is given by the following complete quadratic function of the in-plane stresses.

$$A_1\sigma_{\ell 11}^2 + A_2\sigma_{\ell 22}^2 + A_3\sigma_{\ell 12}^2 + A_4\sigma_{\ell 11}\sigma_{\ell 22} + A_5\sigma_{\ell 11}\sigma_{\ell 12} + A_6\sigma_{\ell 22}\sigma_{\ell 12} + A_7\sigma_{\ell 11} + A_8\sigma_{\ell 22} + A_9\sigma_{\ell 12} = 1 \tag{1}$$

where the σ_ℓ's denote ply stresses at that load condition, the A's denote uniaxial strength coefficients which are initially unknown and are to be determined as will be described later. The subscripts refer to material axes with 1 taken along the fiber direction. It is important to note that equation (1) is not biased. All its terms appear with equal weight. Note also that equation (1) permits for coupling (interaction) between the normal stresses $\sigma_{\ell 11}$ and $\sigma_{\ell 22}$ and the intralaminar shear stress $\sigma_{\ell 12}$. Equation (1) has been referred to in the literature as the strength tensor (ref. 5).

The A's in equation (1) are determined using the following method of least squares matrix equation (ref. 6).

$$\underset{9\times m}{[\sigma_\ell]^T}\ \underset{m\times 9}{[\sigma_\ell]}\ \underset{9\times 1}{\{A\}} = \underset{9\times m}{[\sigma_\ell]^T}\ \underset{m\times 1}{\{1\}} \tag{2}$$

where the σ_ℓ's in equation (2) are the ply stresses at laminate fracture and are computed using laminate theory, and where m is greater than 9 and denotes the number of identical plies for which distinct ply stresses have been computed. By making the following substitutions

$$\underset{9\times 9}{[x]} = \underset{9\times m}{[\sigma_\ell]^T}\ \underset{m\times 9}{[\sigma_\ell]} \tag{3}$$

$$\underset{9\times 1}{\{y\}} = \underset{9\times m}{[\sigma_\ell]^T}\ \underset{m\times 1}{\{1\}} \tag{4}$$

equation (2) can be written thus

$$[x]\ \{A\} = \{y\} \tag{5}$$

where the dimensions have been dropped for convenience.

The A's are determined from equation (5) as follows:

$$\{A\} = [x]^{-1}\{y\} \tag{6}$$

where $[x]^{-1}$ may be determined using any of the standard matrix inverters such as Gauss elimination for example. Once the A's are known, the ply uniaxial fracture stresses (in situ ply strengths) are determined by solving equation (1) for the various special cases (determine its roots), that is by assuming that the ply is subjected to one stress only. For the case where $\sigma_{\ell 11} = S_{\ell 11}$ and $\sigma_{\ell 22} = \sigma_{\ell 12} = 0$, equation (1) reduces to

$$A_1 S_{\ell 11}^2 + A_7 S_{\ell 11} = 1$$

from which the well known quadratic formula yields:

$$S_{\ell 11} = \frac{1}{2A_1}\left[-A_7 \pm \sqrt{A_7^2 + 4A_1}\right] \tag{8}$$

and similarly for the other two in situ ply strengths

$$S_{\ell 22} = \frac{1}{2A_2}\left[-A_8 \pm \sqrt{A_8^2 + 4A_2}\right] \tag{9}$$

$$S_{\ell 12} = \frac{1}{2A_3}\left[-A_9 \pm \sqrt{A_9^2 + 4A_3}\right] \tag{10}$$

COMPOSITE SYSTEMS EXAMINED

The composite systems examined were: E-glass/epoxy (E-G/Epon 826 or E-G/E (ref. 7)), high-modulus graphite/epoxy (Modmor-I/ERLA 4617 or MOD-I/E (ref. 2)), boron/epoxy (boron/epoxy AVCO 5505/4 or B/E (ref. 8)), and low-modulus graphite/epoxy (AS/3501 or AS/E (refs. 3 and 9)). The unidirectional composite (ply) properties of these composite systems are summarized in table I. The reasons for selecting these composite systems are as follows (refer to table I):

1. The E-G/E was selected for its low longitudinal modulus ($E_{\ell 11}$ = 44.1 GPa (6.4 Msi)), its relatively low transverse tensile strength ($S_{\ell 11T}$ = 22.7 MPa (3.6 ksi)), and its relatively low intralaminar shear strength ($S_{\ell 12S}$ = 10.3 MPa (1.5 ksi)).

2. The MOD-I/E was selected for its high $E_{\ell 11}$ (241 GPa (34.9 Msi)), its relatively low $S_{\ell 22T}$ (28 MPa (4.0 ksi)), and the high thermal expansion coefficients difference ($\Delta\alpha = 48\times10^{-6}$ K^{-1} (27×10^{-6} F^{-1})) which tends to produce transply cracks in angleplied laminates when cooling down from cure temperature to room temperature.

3. The B/E was selected for its high $E_{\ell 11}$ (201 GPa (29.2 Msi)), its relatively high longitudinal compressive strength ($S_{\ell 11C}$ = 1592 MPa (231 ksi)) and its relatively high $S_{\ell 12S}$ (55.8 MPa (8.1 ksi)).

4. The AS/E was selected for its intermediate $E_{\ell 11}$ (131 GPa (19.1 Msi)), its low transverse modulus ($E_{\ell 22}$ = 8.6 GPa (1.25 Msi)), and its relatively high $S_{\ell 22T}$ (48 MPa (7.0 ksi)).

5. The extensive amount of laminate fracture stress data available for these composite systems (as will be described below),. which is required to perform a meaningful least squares analysis, was also a consideration.

The laminate fracture stress data for the AS/E, B/E and E-G/E composite systems were obtained from the literature (refs. cited above) while the data for MOD-I/E were generated in-house and reported in reference 2. The various laminate configurations and their corresponding loading conditions are summarized in table II. Note that in this table, the distinct ply stress states at fracture for each laminate and the total ply stress states for the laminates are given in the last two columns. The number of ply stress states for each laminate is obtained by multiplying the number of different plies in each laminate by the number of loading conditions for that laminate. In the case of E-G/E, there were several replicates per test and several tests at combined-loading conditions. In table II only the totals are shown. The interested reader is referred to reference 7 for all the details. As can be seen in table II, a large number of distinct ply stress states is available to evaluate the unknown coefficients (A's) in equation (1). Since there are 9 A's in equation (1), there are about 3 ply stre states per A for the B/E composite system and about 17 for the MOD-I/E.

DETERMINATION OF IN SITU PLY STRENGTHS

The in situ ply strengths for the four composite systems (AS/E, B/E, E-G/E, and MOD-I/E) were determined using the following procedure.

1. The various ply stress states in table II were calculated using the linear laminate analysis available in the Multilayered Filamentary Composite Analysis (MFCA) Computer Code (ref. 10). The use of linear theory for calculating the ply stresses in these laminates is justified because their stress-strain curves to fracture show linear behavior, or very nearly so (refs. 2, 3, 7, and 8). The inputs required in MFCA are: laminate configuration, laminate fracture stress, ply elastic properties ($E_{\ell 11}$, $E_{\ell 22}$, $G_{\ell 12}$ and $\nu_{\ell 12}$, table I), ply thermal expansion coefficients ($\alpha_{\ell 11}$ and $\alpha_{\ell 22}$, table I), and the temperature difference between cure and room temperatures (about 167 K and (300° F) for epoxy composites).

2. The ply stresses calculated in item (1) above for each composite system were used to generate the elements in the $[\sigma_{\ell}]$ array in equation (2). For example, the first row in $[\sigma_{\ell}]$ for the AS/E composite system is the ply stress at fracture in the 0°-ply when the laminate was loaded to fracture along the fiber (0°-ply) direction, or $S^{2}_{\ell 11T}$. Note that each row in $[\sigma_{\ell}]$ will have 1, 2, or 3 non-zero elements corresponding, respectively, to ply stresses $\sigma_{\ell 11}$, $\sigma_{\ell 22}$ and $\sigma_{\ell 12}$. The other rows in $[\sigma_{\ell}]$ are generated in a similar manner. The dimensions for the array $[\sigma_{\ell}]$ are (60×9) for the AS/E composite system (25×9) for B/E, (142×9) for E-G/E and (152×9) for MOD-I/E where the first dimension ((m) eq. (2)) is the total number of ply stress-states corresponding to the last column in table II.

3. The array $[\sigma_{\ell}]$ was transformed to generate the elements in the $[x]$ and in the $\{y\}$ arrays using equations (3) and (4).

4. The coefficients A were evaluated from equation (6) using Gauss elimination.

5. The desired in situ ply strengths were determined using equations (8), (9), and (10) for $S_{\ell 11T}$ and $S_{\ell 11C}$, $S_{\ell 22T}$ and $S_{\ell 22C}$, and $S_{\ell 12S}$, respectively.

The computer program flow chart for the above procedure is illustrated schematically in figure 1. It is important to keep in mind that the in situ ply strengths calculated using this procedure are the best as determined by the method of least squares, where ply fracture stresses from uniaxial and angleplied laminates were used with equal weight. Equation (1) can be used to study the degree of interaction between the normal stresses and the shear stress and other features once the A's have been determined. This is discussed in some detail in the section General Comments and Recommendations.

RESULTS AND DISCUSSION

The relative significance of the coefficients A_5 and A_6 (eq. 1)) which couple the normal ply stresses $\sigma_{\ell 11}$ and $\sigma_{\ell 22}$ with the intralaminar shear ply stress $\sigma_{\ell 12}$, and A_9, which brings in the linear influence of $\sigma_{\ell 12}$, was assessed by solving equation (6) both with and without these coefficients. The results for the AS/E angleplied laminates are summarized in table III. As can be seen, the remaining coefficients are unchanged and, therefore, are independent of the presence of A_5, A_6, and A_9. Similar results were obtained for the corresponding coefficients of the other composite systems. The significant conclusions from these results are: (1) there is no interaction between the in situ ply stresses $\sigma_{\ell 11}$ or $\sigma_{\ell 22}$ and $\sigma_{\ell 12}$; (2) the linear part of $\sigma_{\ell 12}$ does not contribute to the in situ ply combined-stress failure criterion; and (3) the six coefficients (A_1, A_2, A_3, A_7, A_8 (eq. 1)) are sufficient to describe the in situ ply combined-stress failure criterion. In view of this, only these 6 coefficients were used to determine the in situ ply strengths for all four composite systems.

The predicted in situ ply strengths for the four composite systems are summarized in table IV. The corresponding strengths measured from uniaxial tests are also summarized in adjacent columns and the ratios of in situ to uniaxial strengths are given between columns of table IV for comparison purposes. Note that the in situ ply transverse strengths for the MOD-I/E are not given. The reason for this is that the lamination transverse residual stresses

in these angleplied laminates were of sufficient magnitude to cause transply cracks ($\sigma_{\ell 22}/S_{\ell 22T} = 2$) as described in the Composite Systems Examined section. Therefore, the plies could not resist additional stress in the transverse direction and were not permitted to do so in the laminate analysis during the ply fracture stress calculations.

The following are observed from the results in table IV.

(1) The predicted in situ ply longitudinal tensile strength ($S_{\ell 11T}$) is within 10 percent of the uniaxial test value for the AS/E, B/E and E-G/E composite systems; however, that for the MOD-I/E system is 22-percent greater.

2. The predicted in situ ply longitudinal compressive strength ($S_{\ell 11C}$) is within about 10-percent of the uniaxial value for the B/E and E-G/E composite systems, 12-percent greater for the AS/E system, and 35-percent smaller for the MOD-I/E system.

3. The predicted in situ ply transverse tensile strength ($S_{\ell 22T}$) is considerably greater than the uniaxial test data, about 3 times for AS/E, 6 times for B/E and 7 times for E-G/E. As was mentioned earlier, that for the MOD-I/E system was taken to be zero because of the transply crack due to high lamination residual stresses.

4. The predicted in situ ply transverse compressive strength ($S_{\ell 22C}$) is 18-percent less than the uniaxial test data for AS/E, 123-percent higher for the B/E system and 19-percent higher for the E-G/E system. That for MOD-I/E was taken to be zero for the same reasons as for the transverse tensile strength above.

5. The predicted in situ ply intralaminar shear strengths ($S_{\ell 12S}$) are the same as the uniaxial for AS/E, 1-percent less for B/E, 3-times greater for E-G/E, and 64 percent less for MOD-I/E.

A graphical comparison of predicted off-axis tensile strength, using uniaxial and in situ strengths in the combined-stress failure criterion described in reference 11, is shown in figure 2 for all four composite systems. As can be seen the difference between the two off-axis strengths is very significant at higher load angles.

Several important conclusions may be made from the above observations.

1. The in situ ply longitudinal tensile and compressive strengths $S_{\ell 11T}$ and $S_{\ell 11C}$ can be taken to be the same as the uniaxial test data for angleplied laminates which are free of transply cracks as a result of high residual or initial stresses.

2. The in situ ply transverse tensile strength $S_{\ell 22T}$ can be several times higher than the uniaxial data in angleplied laminates free of transply cracks. It follows from this conclusion that calculated laminate strength based on first-ply-failure criteria can be ultra conservative.

3. The in situ ply transverse compressive strength $S_{\ell 22C}$ may be either less than, greater than or about equal to the uniaxial test data in angleplied laminates free of transply cracks. Perhaps uniaxial test methods used to determine this strength need re-examination.

4. The in situ ply shear strength $S_{\ell 12S}$ can be taken to be the same as the uniaxial for high-modulus composite angleplied laminates which are free of transply cracks. However, for E-G/E it can be several times higher than the uniaxial value.

5. Advanced composite angleplied laminates with transply cracks will tend to have a significantly larger in situ ply longitudinal tensile strength $S_{\ell 11T}$ than measured in uniaxial tensile tests, and considerably lower $S_{\ell 11C}$ and $S_{\ell 12S}$.

6. Angleplied laminate designs based on first-ply failure and uniaxial ply strengths will be conservative if no transply cracks are present; they will also be conservative in the presence of transply cracks if the dominant fracture mode is controlled by longitudinal tension; however, these laminates will be unconservative if transply cracks are present and the dominant fracture mode is controlled by either longitudinal compression, or intralaminar shear, or both.

7. The measured values of the uniaxial ply strengths $S_{\ell 22T}$, $S_{\ell 22C}$ and $S_{\ell 12S}$ may be sensitive to the test method used to determine them, and considerable care may be required to determine a correct (reasonable) value for these strengths.

GENERAL COMMENTS AND RECOMMENDATIONS

The present investigation led to several significant results and important conclusions concerning in situ ply strengths. From these, some general comments can be made which may help shed some light on fiber composite angleplied laminate behavior and at the same time stimulate further discussion and research in this area.

The procedure described herein is general enough and can be used when determining in situ ply fatigue life, environmental degradation and not sensitivity. It may also be used to assess the adequacy of present uniaxial strength test data, assuming that the in situ ply strengths are more representative of composite behavior in structural components.

It is generally agreed in the composites community that transply cracks have no effect on fiber-dominant angleplied laminates subjected to monotonic or cyclic tensile loads. However, the results obtained herein show that transply cracks can cause severe reduction in in situ ply longitudinal compression strength and intralaminar shear strength. These reductions may be one of the reasons why advanced fiber composite angleplied laminates tend to exhibit poor compression fatigue resistance (ref. 12) and severe degradation in residual compressive strength of damaged or flawed angleplied laminates (ref. 13). The increase in the in situ ply longitudinal strength ($S_{\ell 11T}$) observed herein, in the presence of transply cracks, may contribute to the increase in residual tensile strength exhibited by advanced angleplied laminates which have been subjected to tensile fatigue (ref. 14).

Though some aspects of the in situ ply strengths such as interaction between normal and shear stresses were investigated herein, several still remain to be examined. Some of these are: the goodness of fit of the combined-stress failure function, the properties of the solid described by the function (principal axes of ellipsoid for example), the degree of interaction between normal stresses ($\sigma_{\ell 11}$ and $\sigma_{\ell 22}$), graphical comparisons of the function obtained herein with those of available failure criteria (similar to fig. 3 for example), sensitivity of the results obtained using available failure criteria and in situ ply strengths as compared

with results obtained using uniaxial strengths, and comparisons of predicted laminate fracture stresses with in situ ply strengths versus measured data.

The procedure described herein can be used to determine the interaction between inplane and out-of-plane ply strengths. For this, out-of-plane stresses produced from flex, short beam shear, and interlaminar stresses at free edges are needed in conjunction with in plane stresses predicted by laminate throy. The in situ ply strengths for other composite systems such as Thornel-300 graphite/epoxy, Kevlar/epoxy, S-glass/epoxy and hybrids should be determined using this procedure. Finally the possibility of using this procedure to characterize the unidirectional composite should be given serious consideration.

CONCLUSIONS

The most significant conclusions of an investigation to obtain an initial assessment of in situ ply strengths are summarized below.

1. The calculated in situ ply strengths can be considerably different from those measured in uniaxial tests, especially those for transverse strength (as much as 7 times greater) and intralaminar shear strength (as much as 3 times greater).

2. The calculated in situ ply compressive and intralaminar shear strengths can be considerably lower (about 30 and 60 percent, respectively) in angleplied laminates with transply cracks; however, the longitudinal tensile strength can be higher (about 20 percent).

3. A computational procedure consisting of laminate analysis in conjunction with the method of least squares can be used to calculate the in situ ply strengths and the degree of interaction between these strengths. This procedure is general and should be equally applicable for use in assessing other in situ ply strength properties such as fatigue, creep, relaxation, notch sensitivity and environmental degradation.

4. The uniaxial ply transverse tensile and compressive strengths and intralaminar shear strength may be sensitive to the test methods used. The current practice for measuring these strengths using uniaxial tests is not representative

of the in situ state. Perhaps a better alternative may be to adopt calculated in situ ply strengths as uniaxial strengths for use in failure load calculations for composite components.

5. The predicted fracture stresses of angleplied laminates, designed using uniaxial strengths, will be conservative if they are free of transply cracks and unconservative if they have transply cracks and are subjected to compressive loads.

6. The in-plane ply normal strength and intralaminar ply shear strength are not coupled in the in situ state.

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TABLE I. - TYPICAL PROPERTIES OF THE UNIDIRECTIONAL COMPOSITES (PLY) USED IN THIS INVESTIGATION

Property	Symbol	Units SI (cust)	Composite			
			Glass/epoxy E-glass/epon 826	High-modulus graphite/epoxy Modmor I/erla 4617 (MOD-I/E)	Boron/epoxy Avco 5505/4 (B/E)	Low modulus graphite/epoxy as/3501 (AS/E)
Density	ρ_{ℓ}	gm/cm^3 (lb/in^3)	0.216 (0.077)	0.163 (0.058)	0.205 (0.073)	0.160 (0.057)
Modulus						
Longitudinal	$E_{\ell 11}$	GPa (Msi)	44.1 (6.4)	241 (34.9)	201 (29.2)	131 (19.1)
Transverse	$E_{\ell 22}$	"	13.8 (2.0)	7.7 (1.12)	22.1 (3.2)	8.60 (1.25)
Shear	$G_{\ell 12}$	"	4.1 (0.6)	6.1 (0.89)	5.4 (0.78)	3.73 (0.54)
Poisson's ratio						
Major	$\nu_{\ell 12}$	------	0.32	0.27	0.17	0.30
Thermal exp. coef.						
Longitudinal	$\alpha_{\ell 11}$	$10^{-6}K^{-1}$ ($10^{-6}F^{-1}$)	3.8 (2.1)	-0.9 (-0.5)	6.1 (3.4)	-0.56 (-0.31)
Transverse	$\alpha_{\ell 22}$	"	36 (20.0)	46.8 (26)	30.4 (16.9)	2.3 (0.13)
Strength						
Long. tensile	$S_{\ell 11T}$	MPa (ksi)	827 (120)	563 (81.7)	1371 (199)	1630 (236)
Long. compres.	$S_{\ell 11C}$	"	356 (51.7)	456 (66.2)	1592 (231)	1050 (152)
Transv. tensile	$S_{\ell 22T}$	"	10.3 (1.5)	28 (4.0)	55.8 (8.1)	48 (7)
Transv. comp.	$S_{\ell 22C}$	"	62.7 (9.1)	200 (29.0)	128 (17.9)	255 (36.9)
Intral. shear	$S_{\ell 12S}$	"	22.7 (3.6)	51 (8.0)	62.7 (9.1)	66 (9.6)
Ply thickness	t_{ℓ}	cm (in.)	0.021 (0.0084)	0.019 (0.0075)	(0.005)	0.014 (0.0055)

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TABLE II. - SUMMARY OF PLY STRESS STATES USED IN THE ANALYSIS

Composite system and laminate configuration	Laminates loaded to fracture in					Number of ply stress states at fracture	
	Tension		Shear	Compression			
	X	Y	XY	X	Y	Per laminate	Total per system
[1]Graphite/epoxy AS/3501 (AS/E)							
$[0_8]$	x	x	x	x	x	5	
$[0/\pm 45/0/\pm 45]_S$	x	x	x	x	x	15	60
$[0_2/\pm 45/0_2/90/0]_S$	x	x	x	x	x	20	
$[(0/\pm 45/90)_2]_S$	x	x	x	x	x	20	
[1]Boron/epoxy 5505/4(B/E)							
$[0_8]$	x	x	x	x	x	5	25
$[0/\pm 45/90]_S$	x	x	x	x	x	20	
[2]E-Glass/epoxy (E-G/E)							
$[0_6]$	x	x	x	x	x	12	
$[(\pm 30)_2]_S$	x	x	x	x	x	20	
$[(\pm 45)_2]_S$	x	x	x	x	x	40	142
$[(\pm 60)_2]_S$	x	x	x	x	x	30	
$[90_6]$	x	x	x	x	x	40	
[3]Graphite/epoxy MOD-I/ERLA 4617 MOD-I/E							
$[0_8]$	x	x	x	x	x	5	
$[0/\pm 60]_S$	x					21	
$[0/\pm 45/90]_S$	x					28	152
$[0/\pm 30/\pm 60/90]_S$	x					42	
$[0/\pm 22.5/\pm 45/\pm 67.5/90]$	x					56	

[1]Flat specimens subjected to uniaxial load.
[2]Thin tubes subjected to uniaxial and combined loads (with replicates).
[3]Flat specimens subjected to uniaxial loads at 0°, 15°, 30°, 45°, 60°, 75° and 90° to 0-ply.

TABLE III. - COMPARATIVE VALUES OF THE A_i COEFFICIENTS IN EQ. (1) FOR THREE DIFFERENT EVALUATION CONDITIONS

Evaluation condition	Coefficients normalized with respect to A_1^*								
	A_1/A_1	A_2/A_1	A_3/A_1	A_4/A_1	A_5/A_1	A_6/A_1	A_7/A_1 kPa/(ksi)	A_8/A_1 kPa/(ksi)	A_9/A_1 kPa/(ksi)
$A_i \neq 0$	1.0	51.8	407	-10.0	1111	-926	-281 (-40.7)	2551 (370)	460 (66.7)
$A_5 = A_6 = 0$	1.0	51.8	407	-10.0	0	0	-281 (-40.7)	2551 (370)	434 (62.9)
$A_5 = A_6 = A_9 = 0$	1.0	51.8	407	-10.0	0	0	-281 (-40.7)	2551 (370)	0

$^*A_1 = 0.57\times10^{-6}\ \mathrm{MPa}^{-2}\ (0.27\times10^{-4}\ (\mathrm{ksi})^{-2})$.

TABLE IV. - SUMMARY OF PREDICTED IN SITU PLY STRENGTHS, UNIAXIAL DATA AND RATIO OF IN SITU T('NIAXIAL STRENGTH

Ply strength ratio (in situ/uniaxial)	Ply strengths kPa/(ksi)/ratio in situ/uniaxial							
	Graphite/epoxy AS/3501 (AS/E)		Boron/epoxy 5505/4 (B/E)		E-glass/epoxy E-G/epon 826 (E-G/E)		Graphite/epoxy MOD-I/erla 4617 (MOD-I/E)	
	In situ	Uniaxial	In situ	Uniaxial	In situ	Uniaxial	In situ	Uniaxial
Long. tension, $S_{\ell 11T}$	1480 (214)	1630 (236)	1380 (199)	1380 (199)	870 (126)	828 (120)	690 100	566 (82)
Ratio	0.91		1.00		1.05		1.22	
Long. compression, $S_{\ell 11C}$	1170 (170)	1050 (152)	1450 (210)	1600 (232)	341 (49.4)	357 (51.7)	298 43.2	455 (66)
Ratio	1.12		0.91		0.96		0.65	
Transv. tension, $S_{\ell 22T}$	144 (20.9)	48 (7.0)	334 (48.4)	56 (8.1)	72 (10.4)	11 (1.53)	----	28 (4.0)
Ratio	2.99		5.98		6.80		----	
Transv. compres., $S_{\ell 22C}$	208 (30.2)	255 (36.9)	270 (39.1)	124 (17.9)	75 (10.8)	63 (9.1)	----	197 (28.6)
Ratio	0.82		2.23		1.19		----	
Intralam. Shear, $S_{\ell 12S}$	66 (9.6)	66 (9.6)	64 (9.2)	62 (9.1)	74 (10.7)	24 (3.51)	20 (2.9)	55 (8.0)
Ratio	1.00		0.99		3.05		0.36	

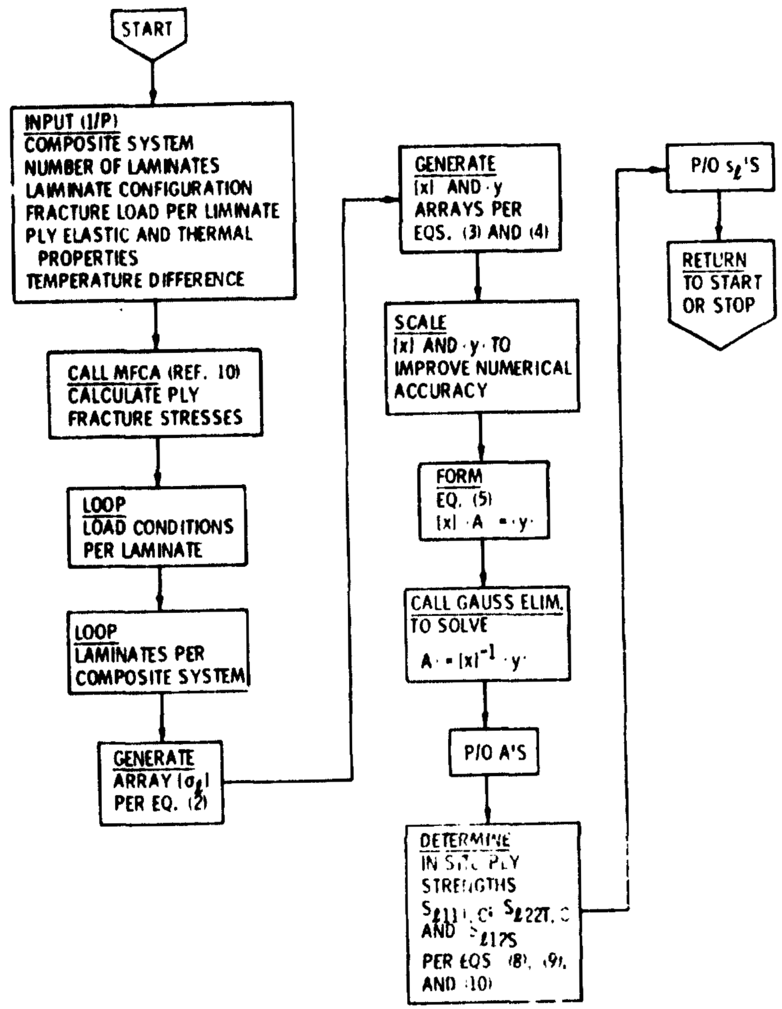

Figure 1. Flow chart for a procedure to determine the in situ ply strengths.

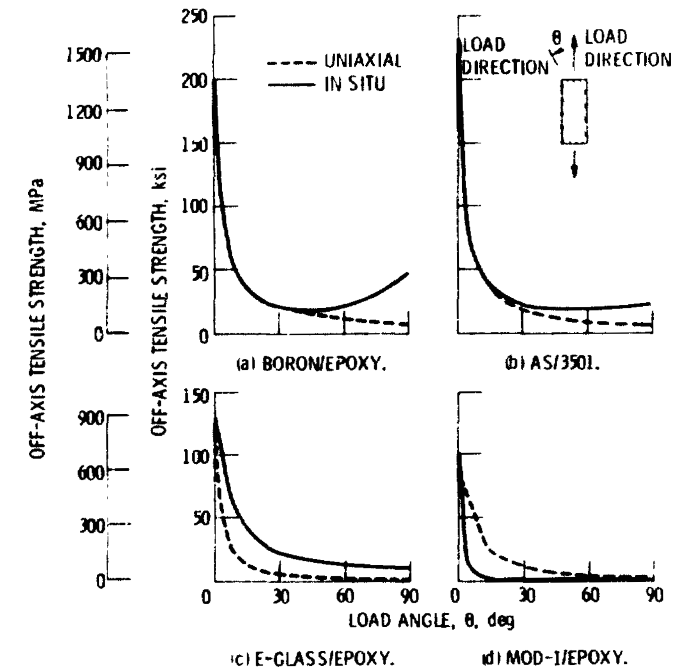

Figure 2. - Predicted off-axis tensile strength using uniaxial and in-situ ply strengths.